Demonstration of Lunar Ice Miner System Components

SPACE RESOURCE ROUNDTABLE, JUNE 6th-9th

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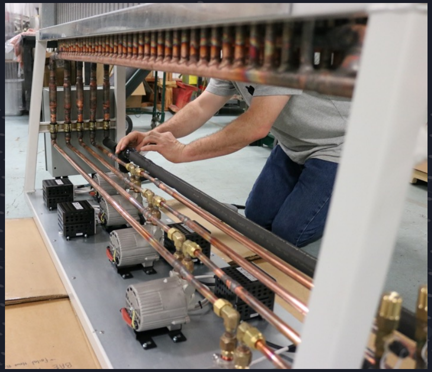

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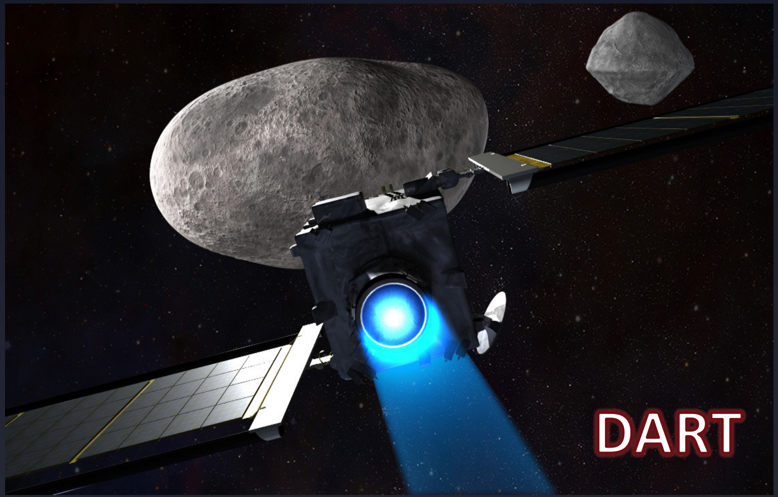

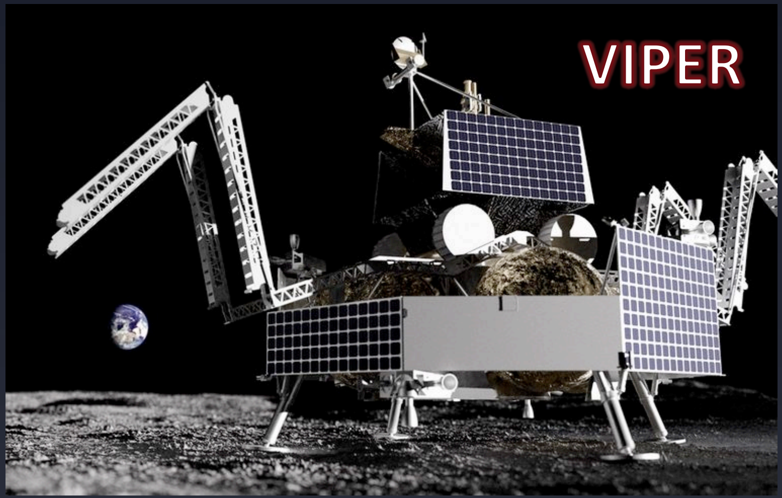

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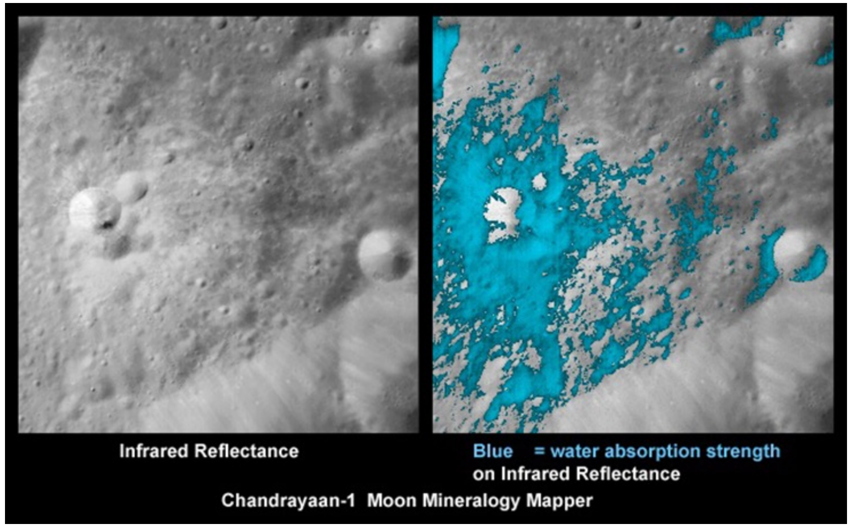
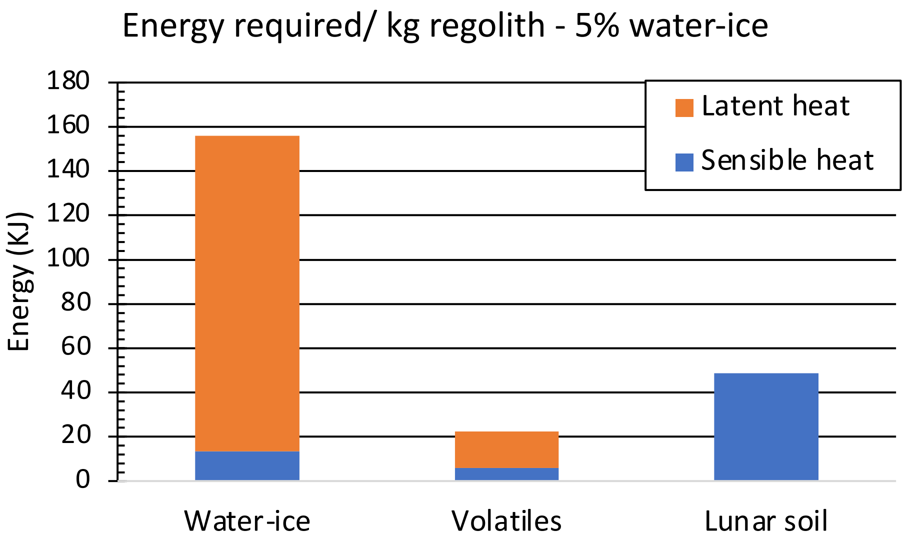
Ice Mining For Lunar ISRU

- Sustaining future space explorations including those on the moon depend vastly on ISRU activities
- Water-ice is a valuable resource available on lunar south pole (in PSR)
  - About 600 million tons of water is estimated to be trapped within the lunar soil
  - Mean concentration of water-ice: 5% by mass
- Lunar conditions are vastly different from Earth
  - Pressure: < 1E-10 Torr
  - Temperature: 40 K to 80 K

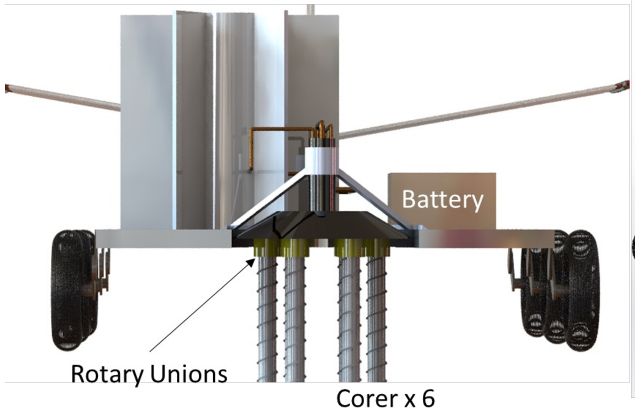


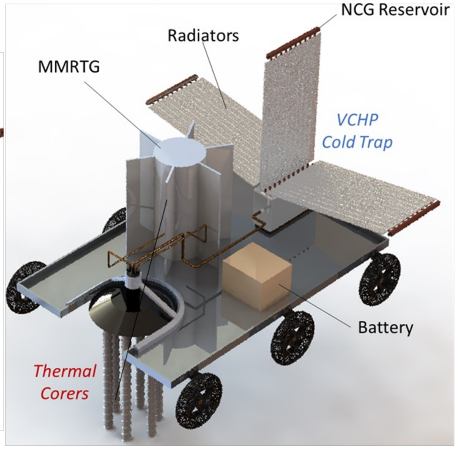


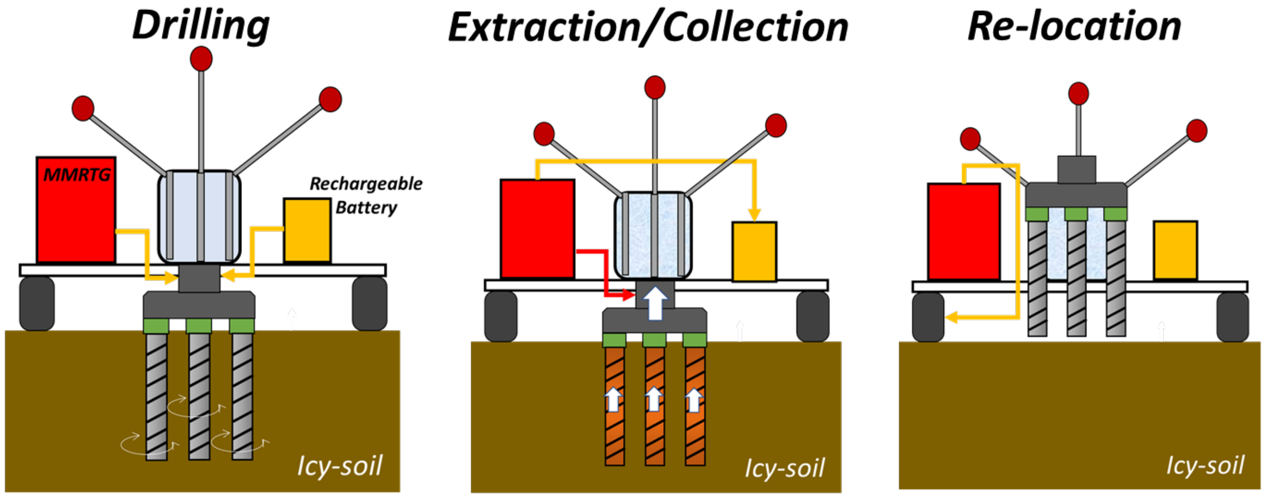
- Thermal mining of ice consumes a total of 227 kJ of energy per kg of soil
- An example case: 10 mT O_2 → 15 mT H_2O/225 days → 2.78 kg/h
- Total thermal energy required for ice extraction is 3.5 kWh (70% used for sublimation)
- To resublimate vapor to ice, 2.5 kWh energy must be rejected

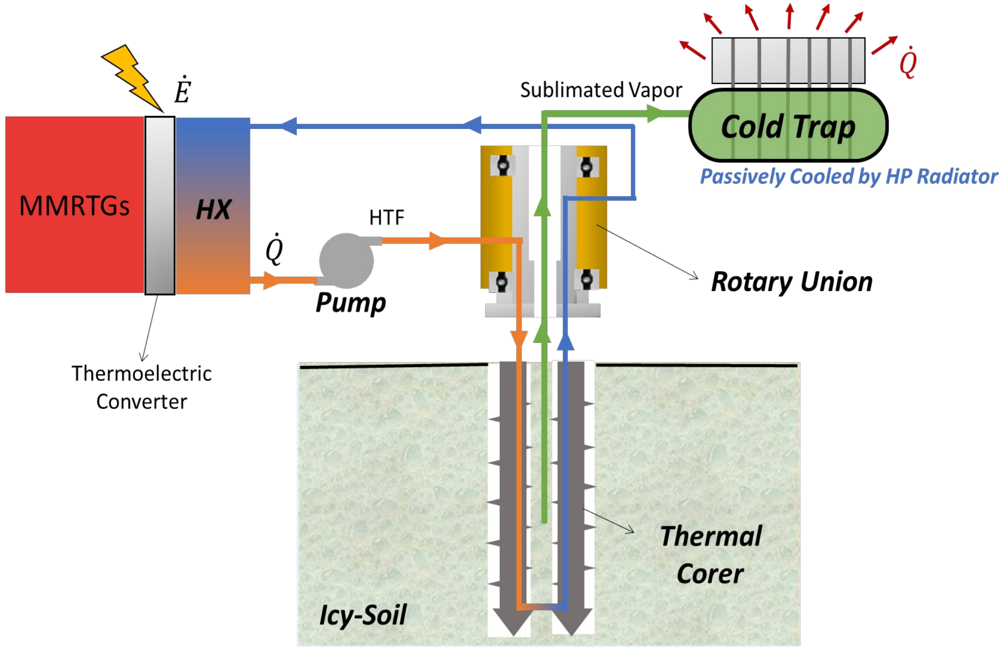
Thermal Management System for Lunar Ice Miner

- ACT with HBR is developing a thermal management system for ice mining: extraction & collection
- The thermal energy for extraction is based on utilizing waste heat from onboard power source like MMRTG







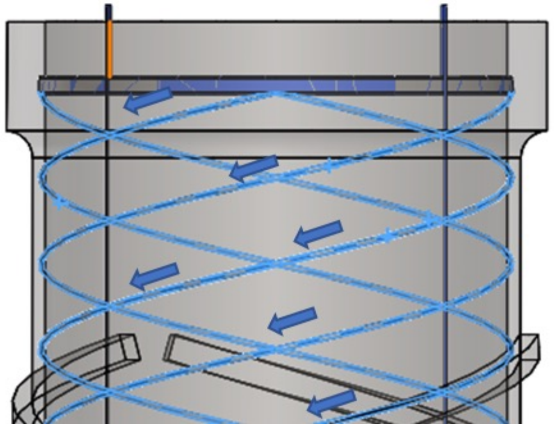


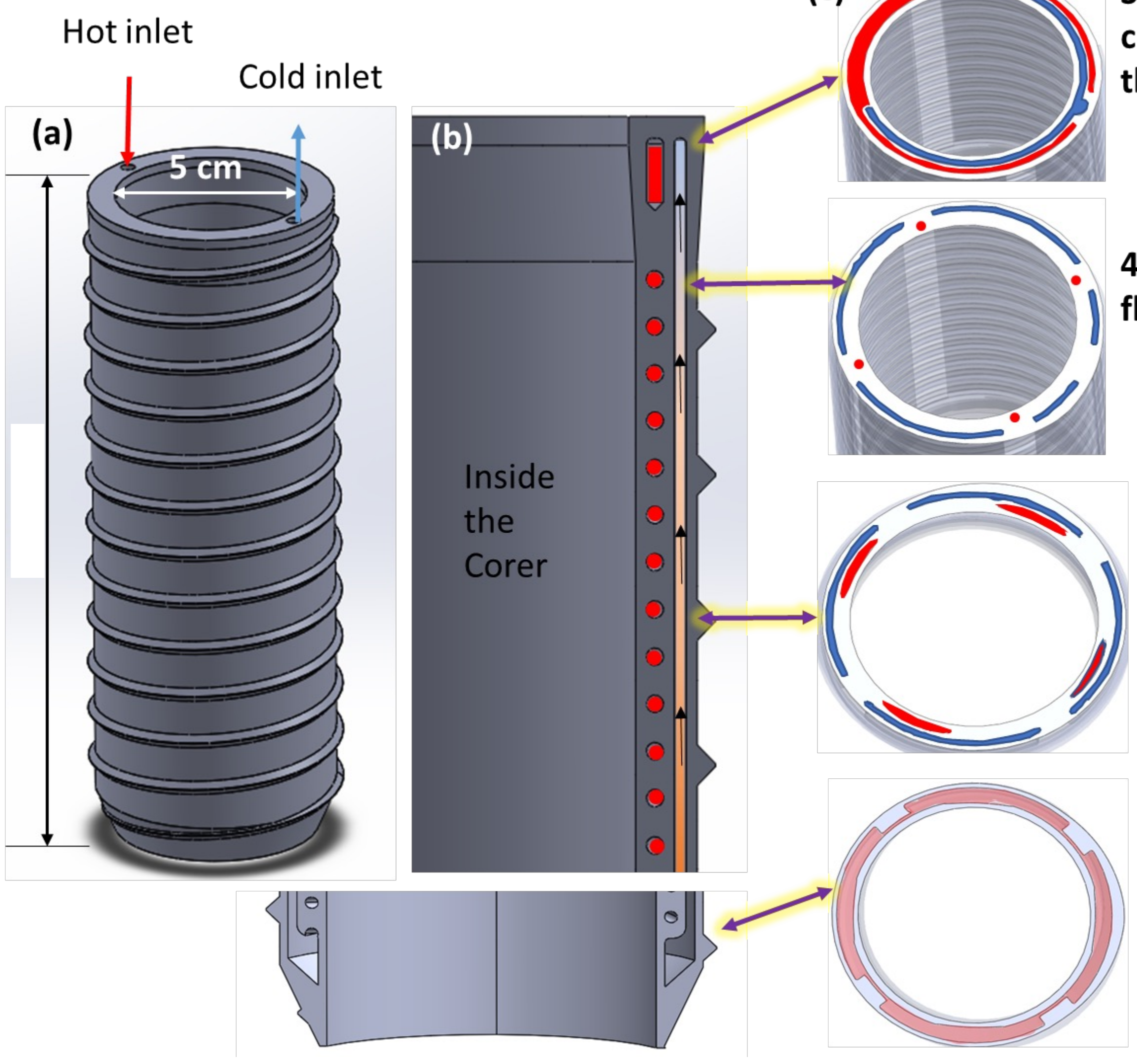
Concept of operations of system components

Thermal Corer

Thermal corer is essentially a mechanical auger with integrated minichannels to facilitate heat transfer.

Top manifold



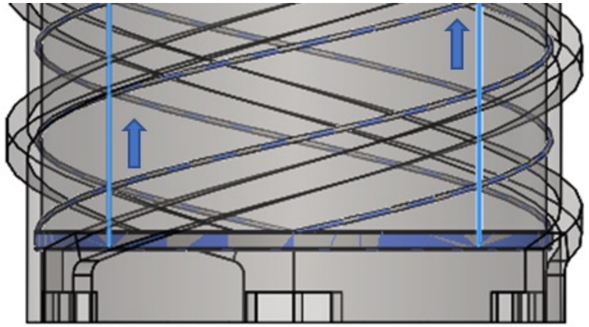


Splitting of incoming and outgoing channels along the annular space at the top of the thermal corer

4 minichannel spiral passages for hot fluid to flow downwards

Hot fluid spiral passages growing in size axially downwards

Minichannel and annular flow passages converging at the bottom for flow reversal



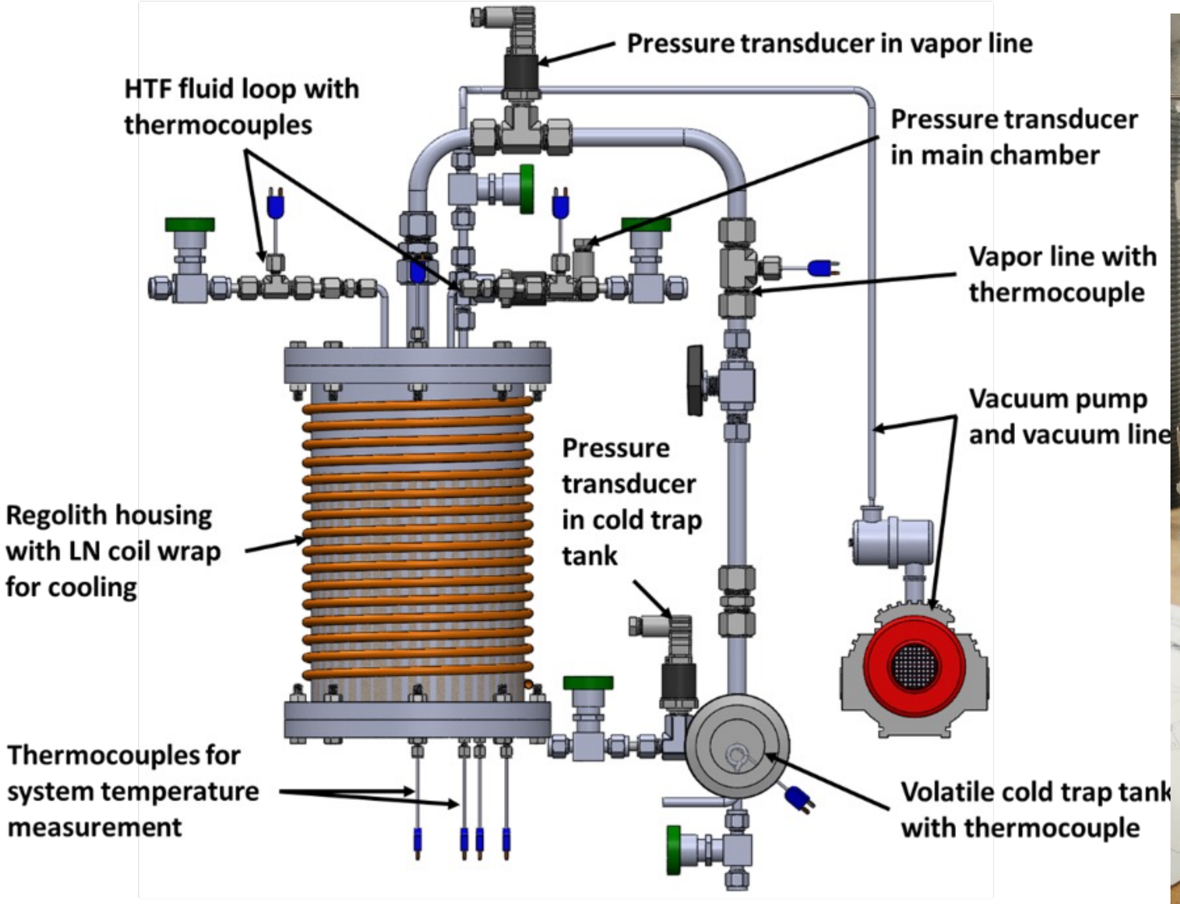
Bottom manifold

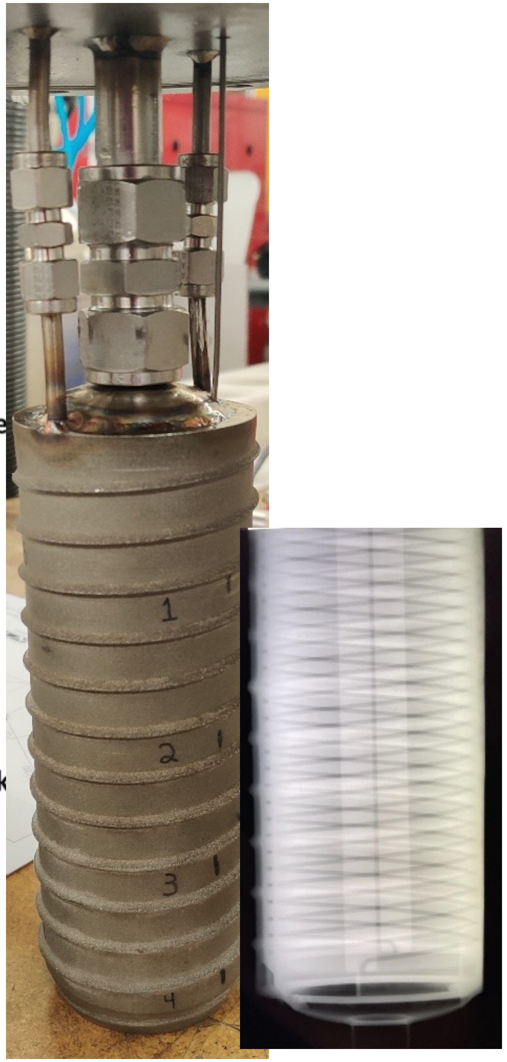
Experimental System for Ice Extraction with Thermal Corer

Test setup consists of

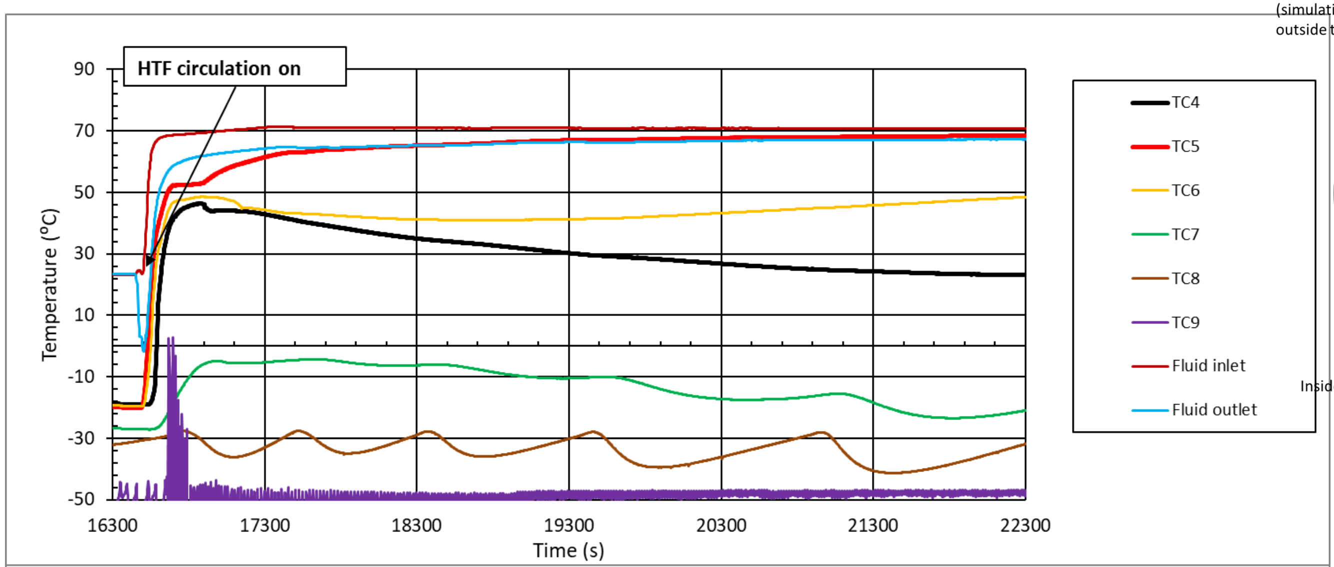
- ❑ **Regolith chamber**: to simulate icy-regolith environment
- ❑ **Thermal corer**: sub-scale prototype. 5 cm ID and 17.3 cm long made with SS316
- ❑ **Cold trap tank**: for vapor deposition as ice
- ❑ **Vapor line**: to connect regolith chamber to cold trap tank
- ❑ **Vacuum pump**: for vacuuming the system
- ❑ Thermocouples and pressure transducers

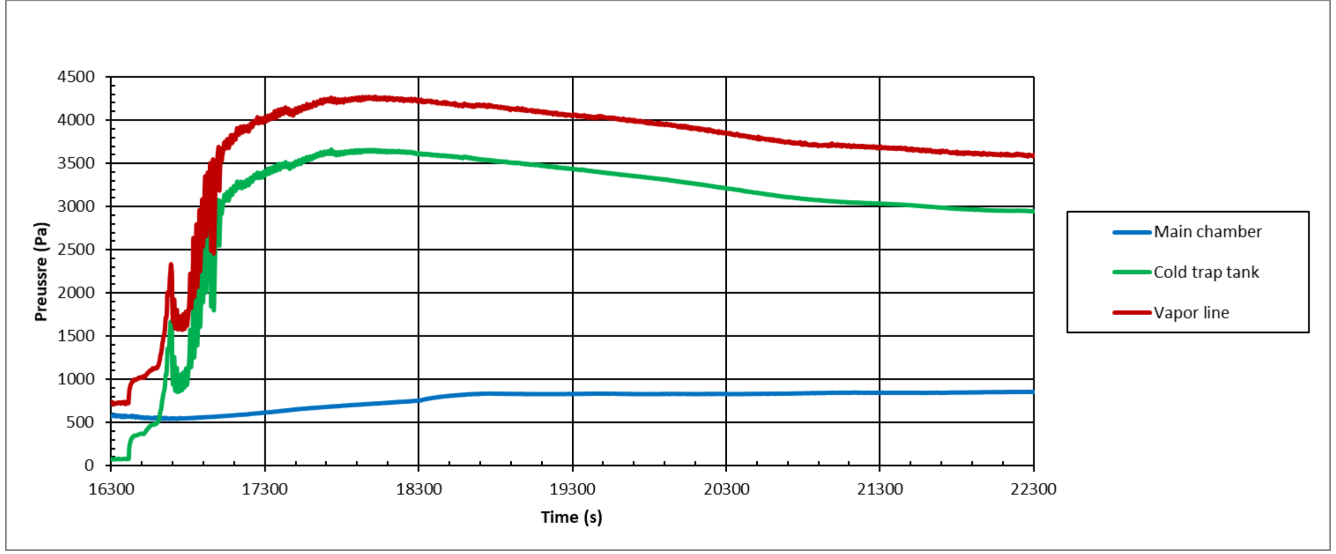
Schematic of the experimental system

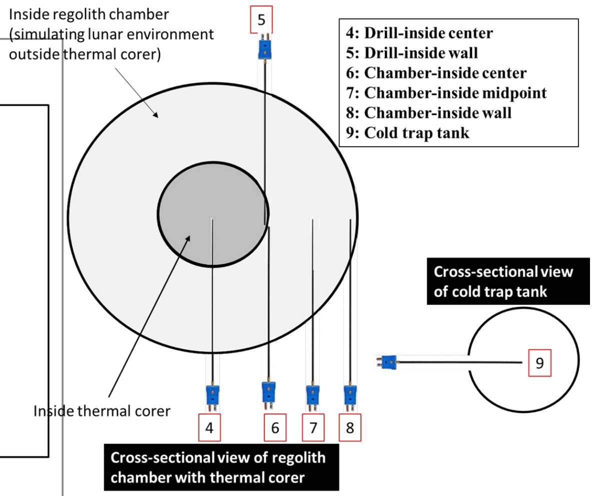




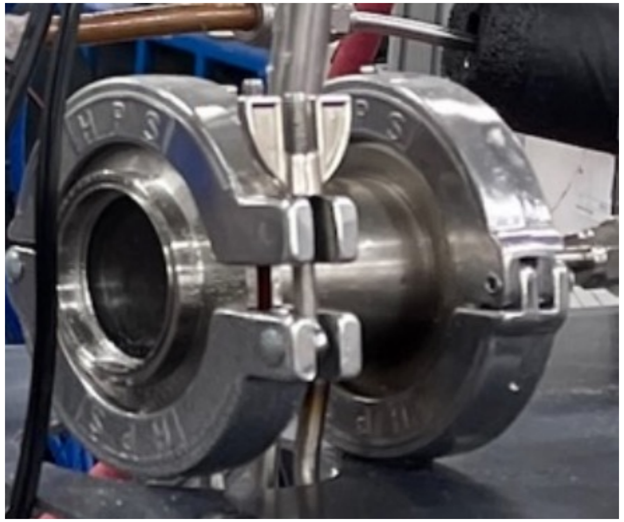
Ice-Extraction with sub-scale Thermal Corer Prototype







Small cold trap tank
Volume: ~110 cc

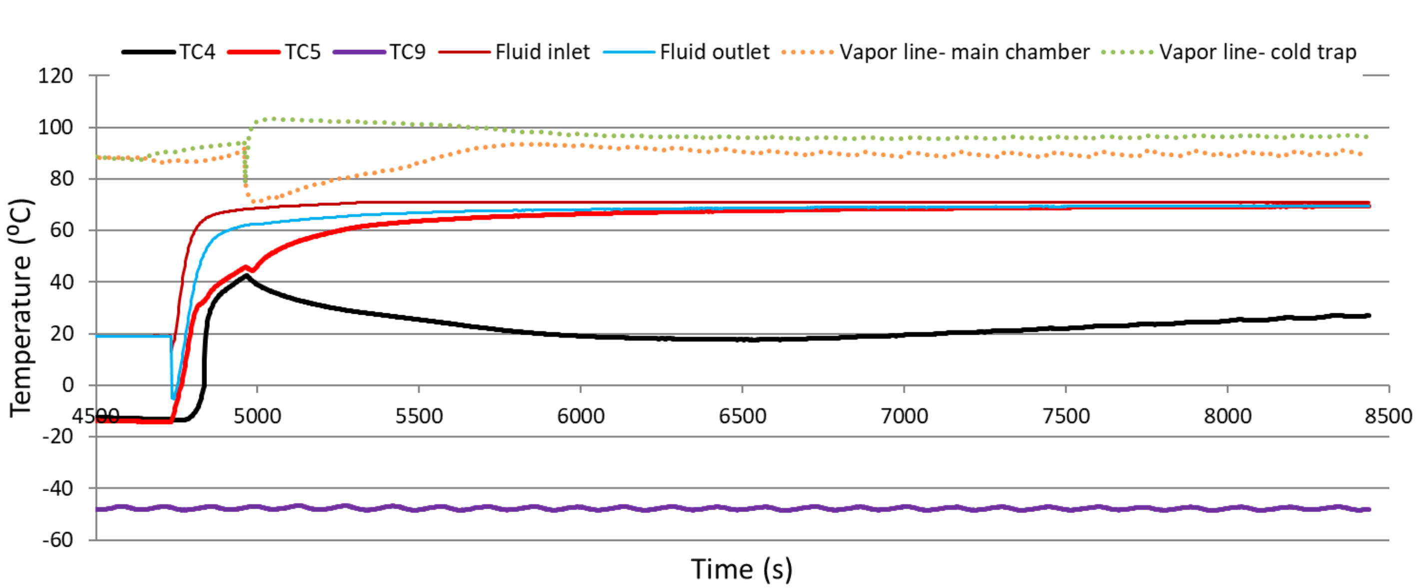


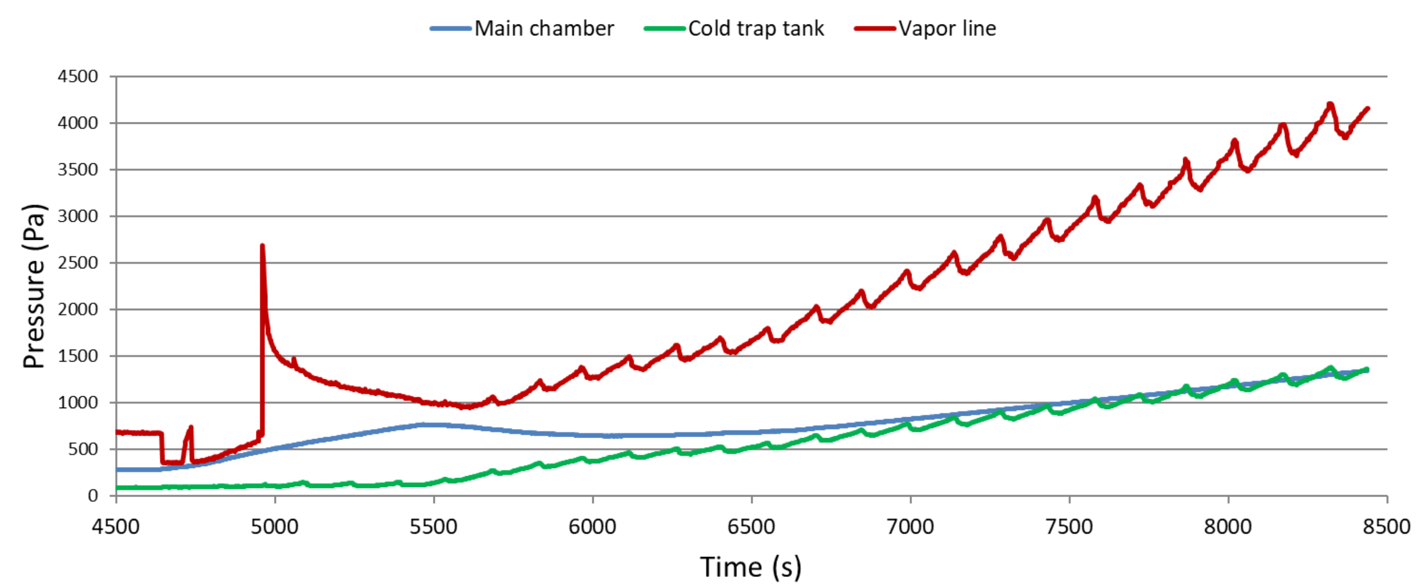
- Experimental conditions: Pressure < 0.01 Torr
- HTF temperature: 75 °C
- Maximum ice extraction occurred within 15-20 mins
- Ice extraction rate decreased after that point
- Cold trap tank for ice collection had inner volume of ~ 110 cm^3→ resulted in fast increase in tank (back) pressure, by **> 3000 Pa in 15 mins**

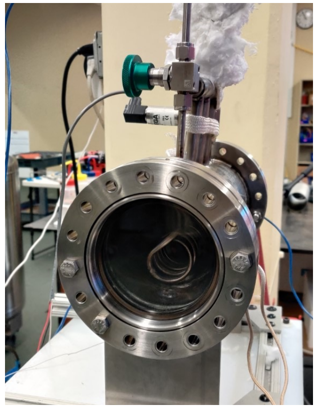
Visualizing Ice-Deposition in the Cold Trap Tank

- About 12 grams of water-ice extracted by the thermal corer in one hour
- Ice deposition rate decreases after ~20 mins
- As a design improvement a larger volume cold trap tank included to counteract large pressure increase rate in the tank

Ice-Extraction with Thermal Corer: Inclusion of Larger Cold Trap Tank



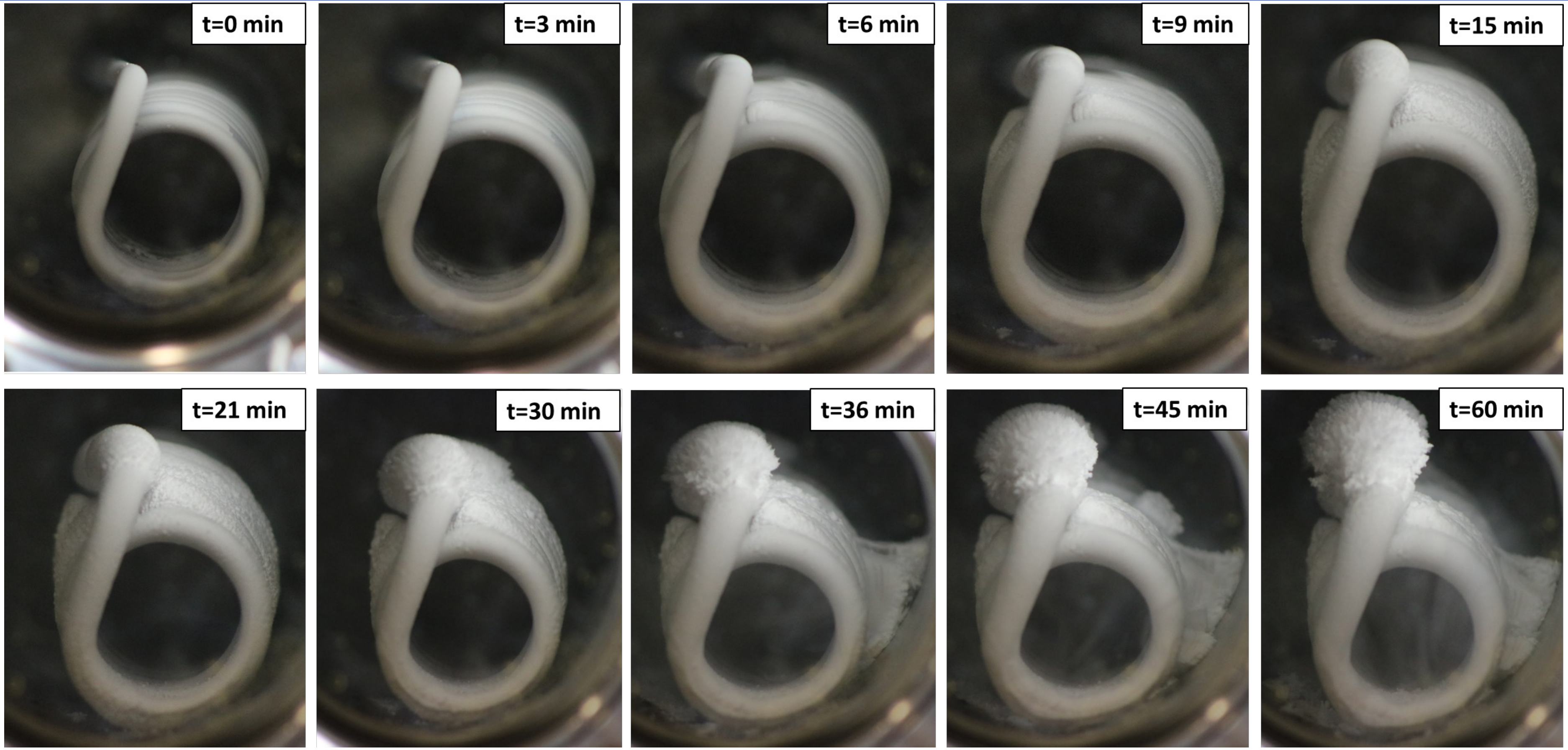




Larger cold trap tank
Volume: ~2100 cc
About 19X larger than previously used cold trap tank

- ❑ Another design change: the vapor line was kept at a higher temperature to avoid condensation of vapor along the vapor line
- ❑ A transient unsteady period observed initially due to low temperature vapor generation (as seen by vapor line) and ice deposition in cold trap tank
- ❑ Pressure increase rate in the cold trap tank was significantly lower (**< 1500 Pa/hour**) compared to smaller tank.
- ❑ About 32 grams of ice deposited in the cold trap tank

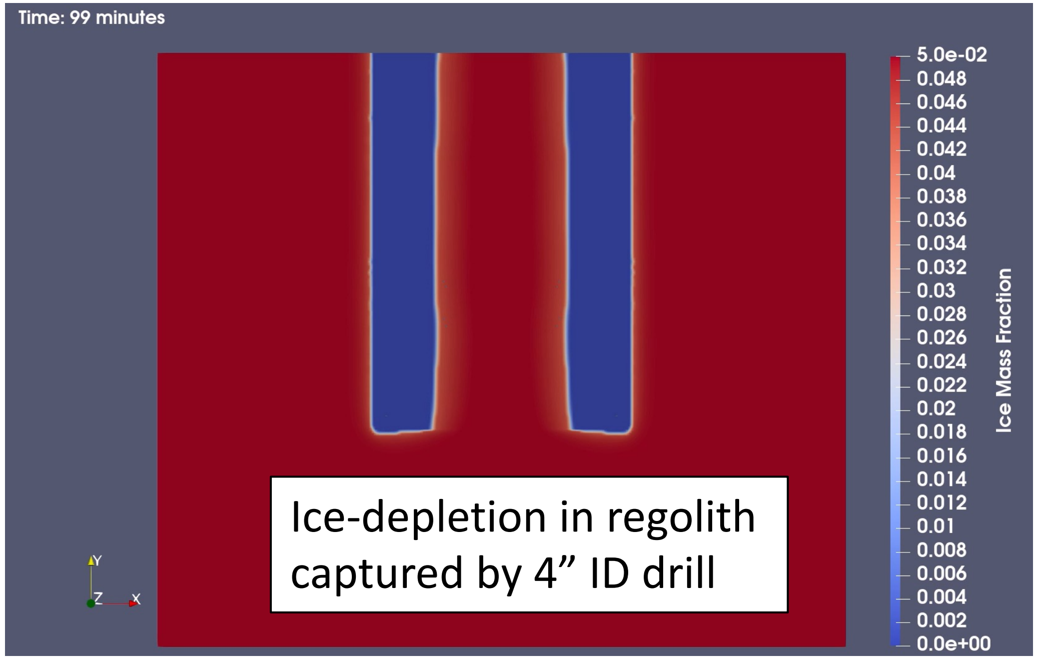
Visualizing Ice Deposition in the Cold Trap Tank

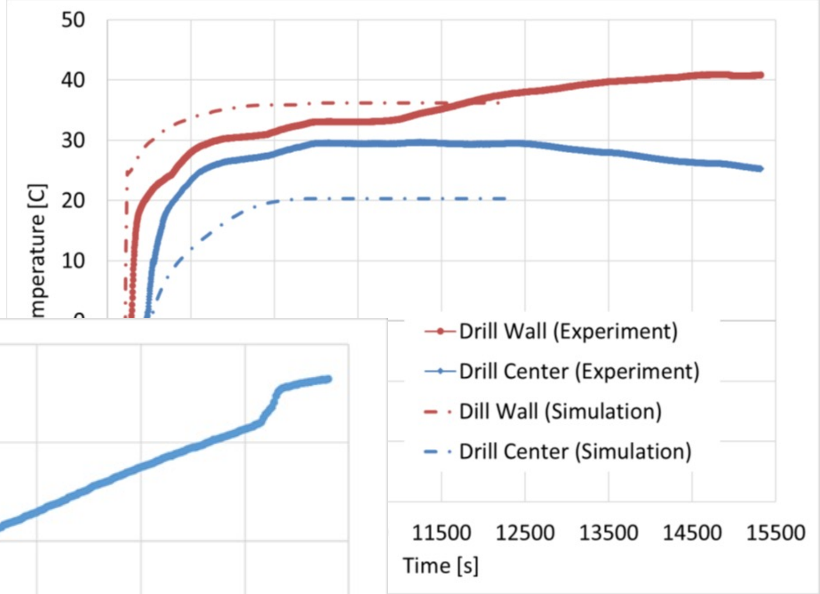


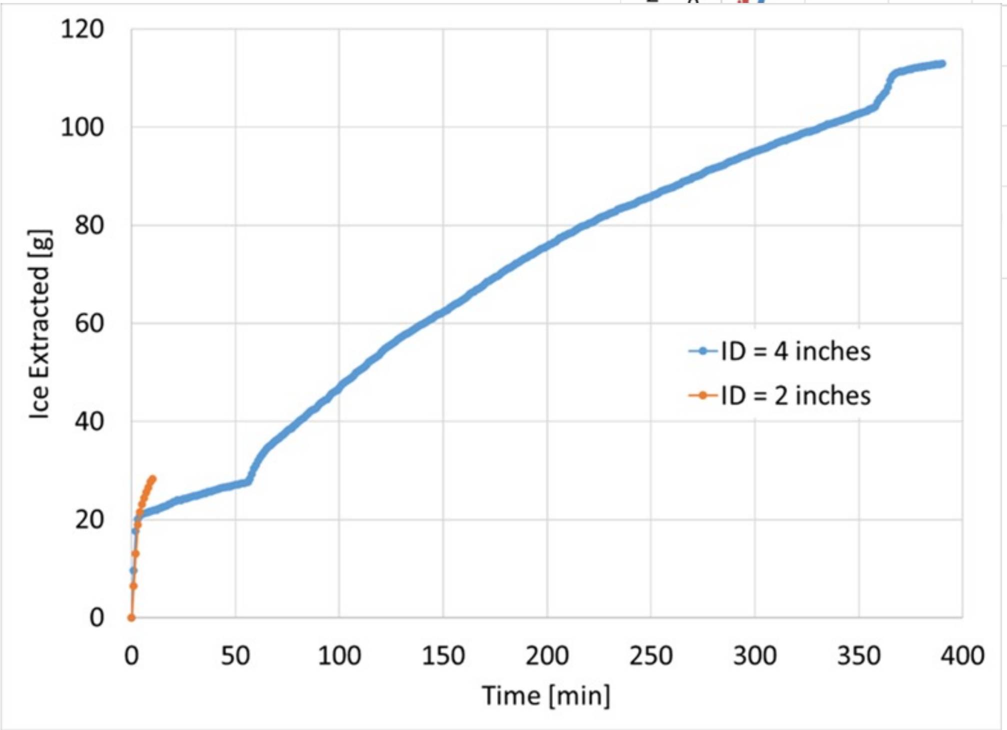
- 32 grams of ice was extracted (> 100% of capture)
- Initial deposition of ice in the tank during preparation estimated at ~ 3 grams
- Overestimation could be due to: Initial deposition included in total ice capture mass; uncertainty in ice fraction in the soil during preparation

Numerical Model

- A conduction based numerical model was developed with experimental correction factors
- Reasonable match with experimental data obtained
- Model extended to compare performance of a 2” ID drill against 4” ID drill

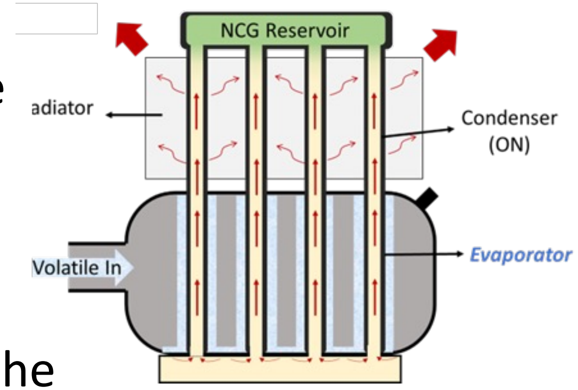


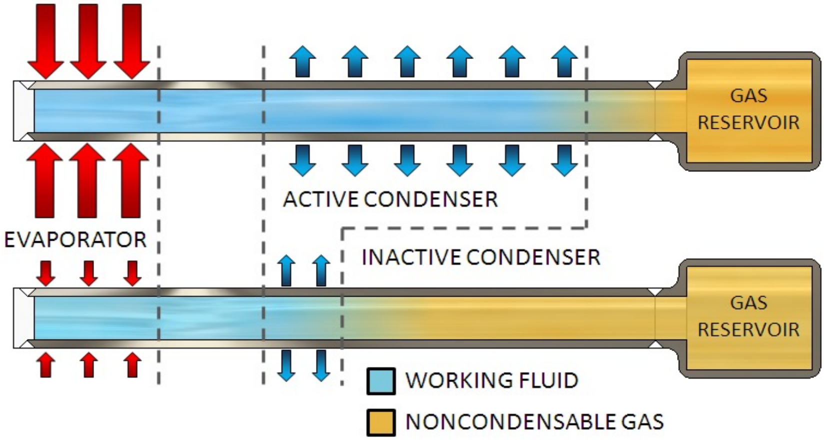


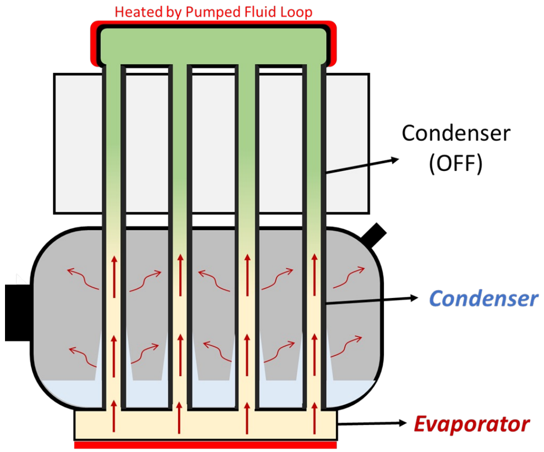


Variable Conductance Heat Pipe (VCHP) Based Cold Trap Tank

- VCHP: Has a Non-Condensable Gas (NCG) column that can be modulated to regulate heat transfer to the condenser
- Heat pipe mode: NCG is in reservoir and condenser is fully active
- VCHP mode: NCG partially or fully blocks the condenser

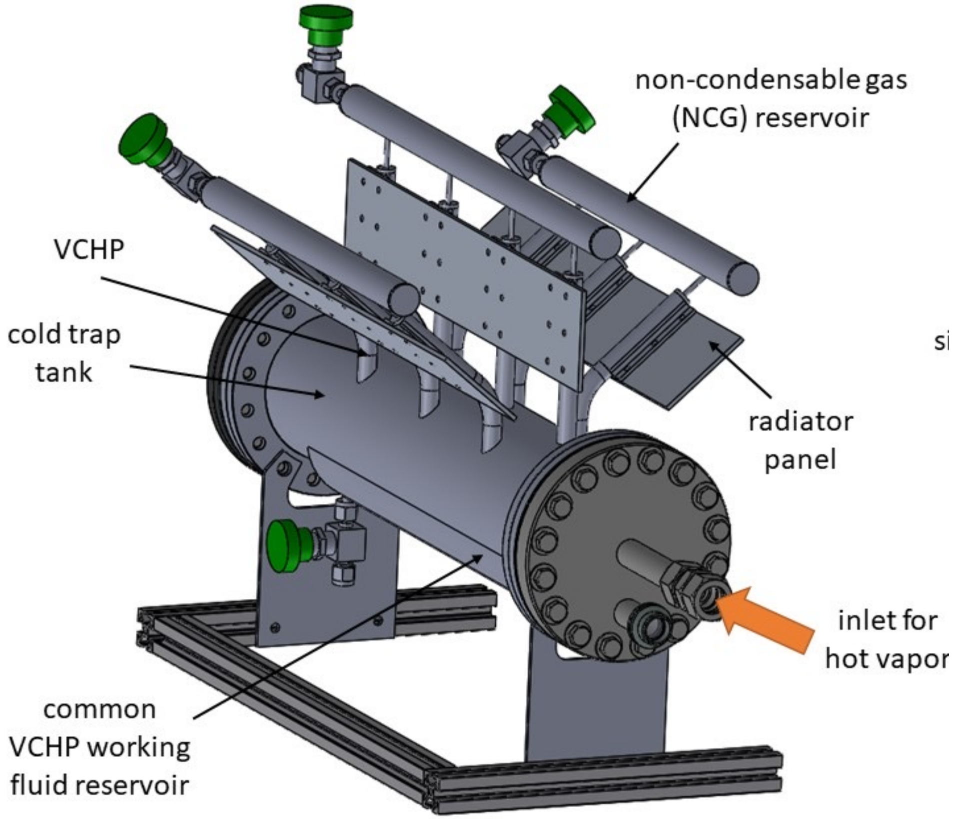




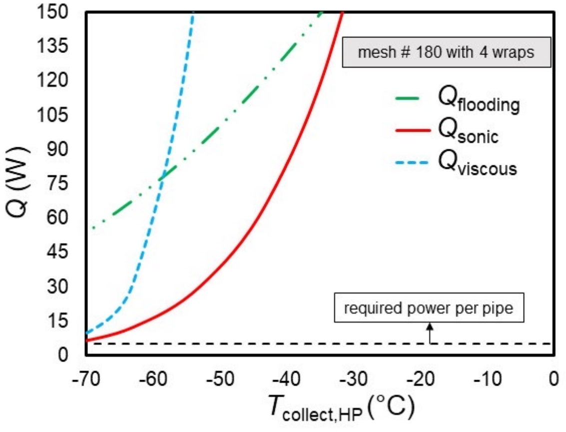


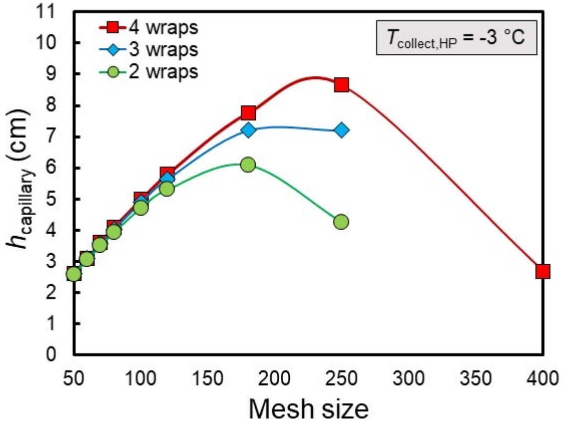
- **Ice-collection**
- Sublimated hot vapor deposits as ice on the heat pipe surface
- The heat is extracted and rejected to ultimate heat sink
- NCG reservoir is in reservoir
- **De-icing**
- Thick ice-layer must be de-iced
- NCG reservoir is heated by the pumped fluid loop
- NCG fills heat pipe in the radiator and blocks heat rejection
- Heat pipe surface in the cold trap tank becomes condenser and heat is applied at the bottom reservoir for de-icing

Design Analysis of VCHP Cold Trap Tank



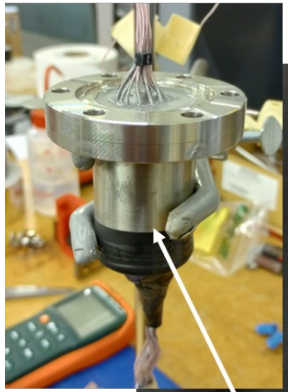
Heat pipe		Wick structure (calculations)	
Evaporator length	3.87" (commercial tank size)	Material	SS
Adiabatic length	1.75"	Mesh number	180
Condenser length	2.53"	Number of wraps	4
Outer diameter (OD)	0.5"		
Wall thickness	0.035"		
Inner diameter (ID)	0.43"		



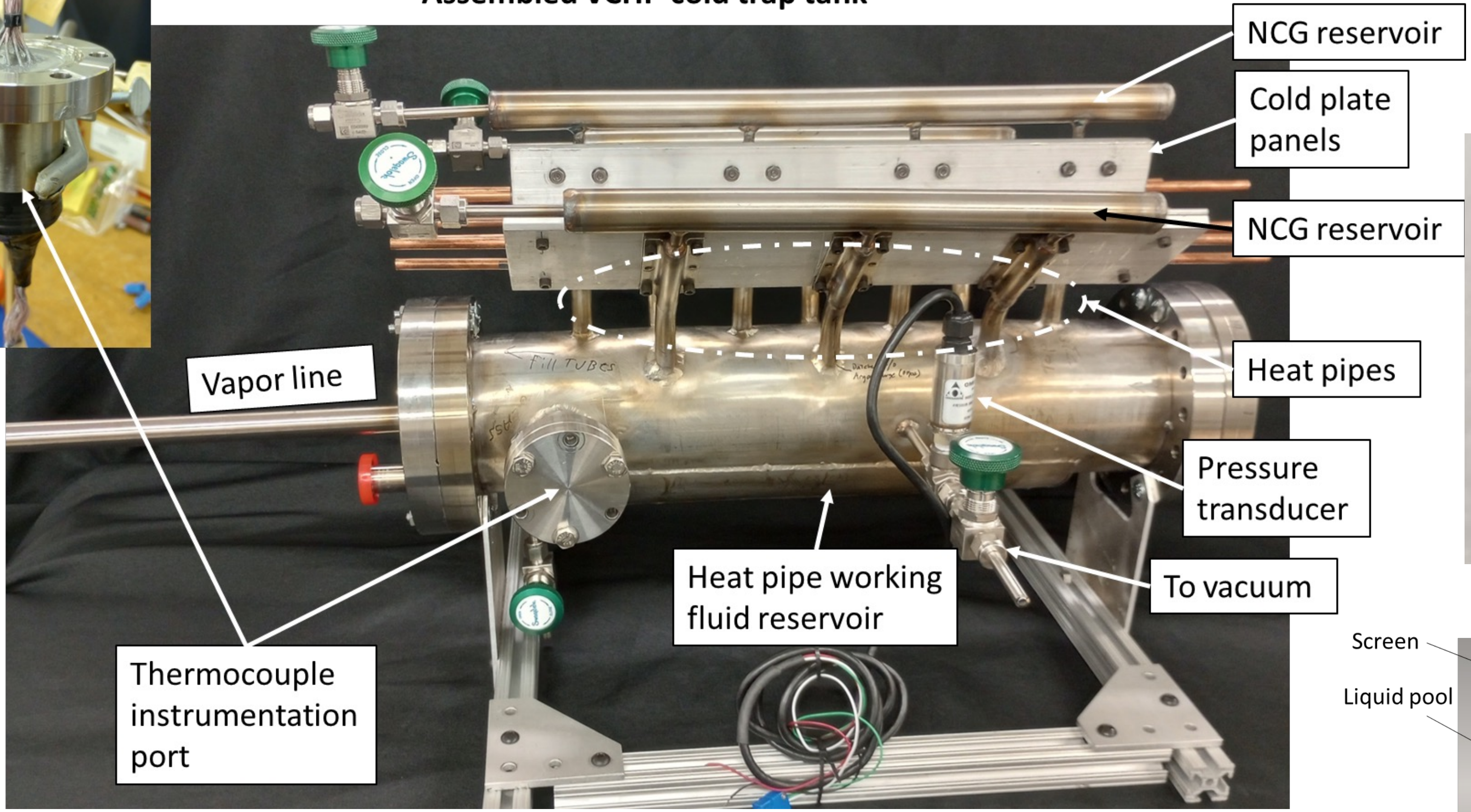


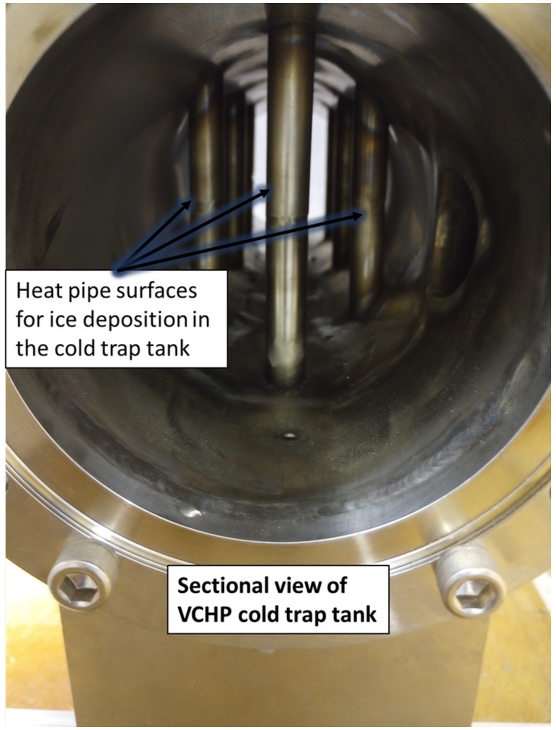
- ❑ The heat pipe operates typically in the range: -90 °C to 0 °C
- ❑ From in-house modeling tools, acetone found to be a suitable working fluid.
- ❑ Cold trap tank with 10 heat pipes designed along with an intermediary "balcony" structure to support capillary rise of fluid

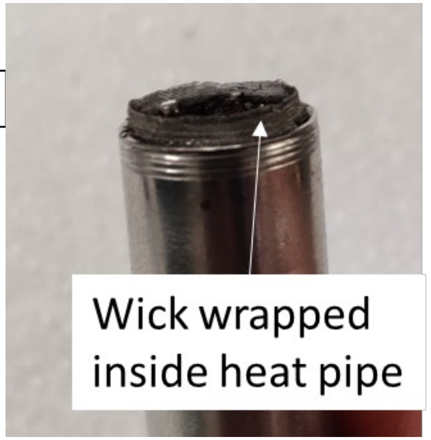
Assembled VCHP Cold Trap Tank

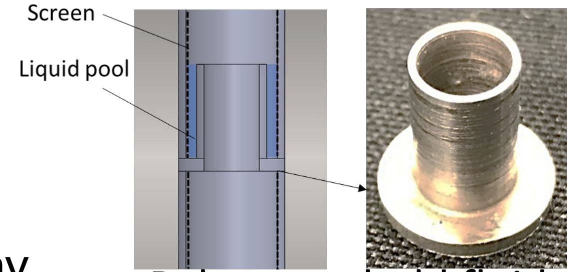


Assembled VCHP cold trap tank









Balcony to hold fluid

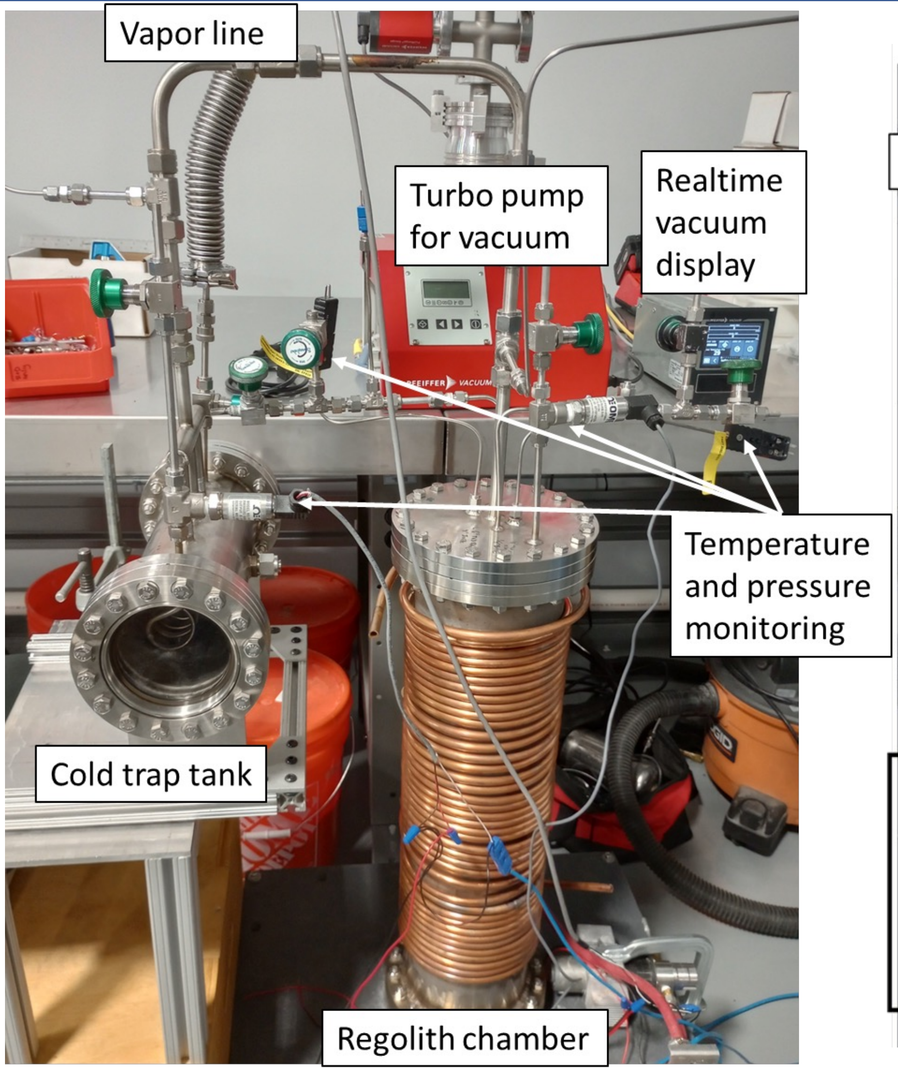
- ❑ Functionality testing of the VCHP cold trap tank underway
- ❑ Currently using cold plates (with LN circulation) to simulate cold radiator panels

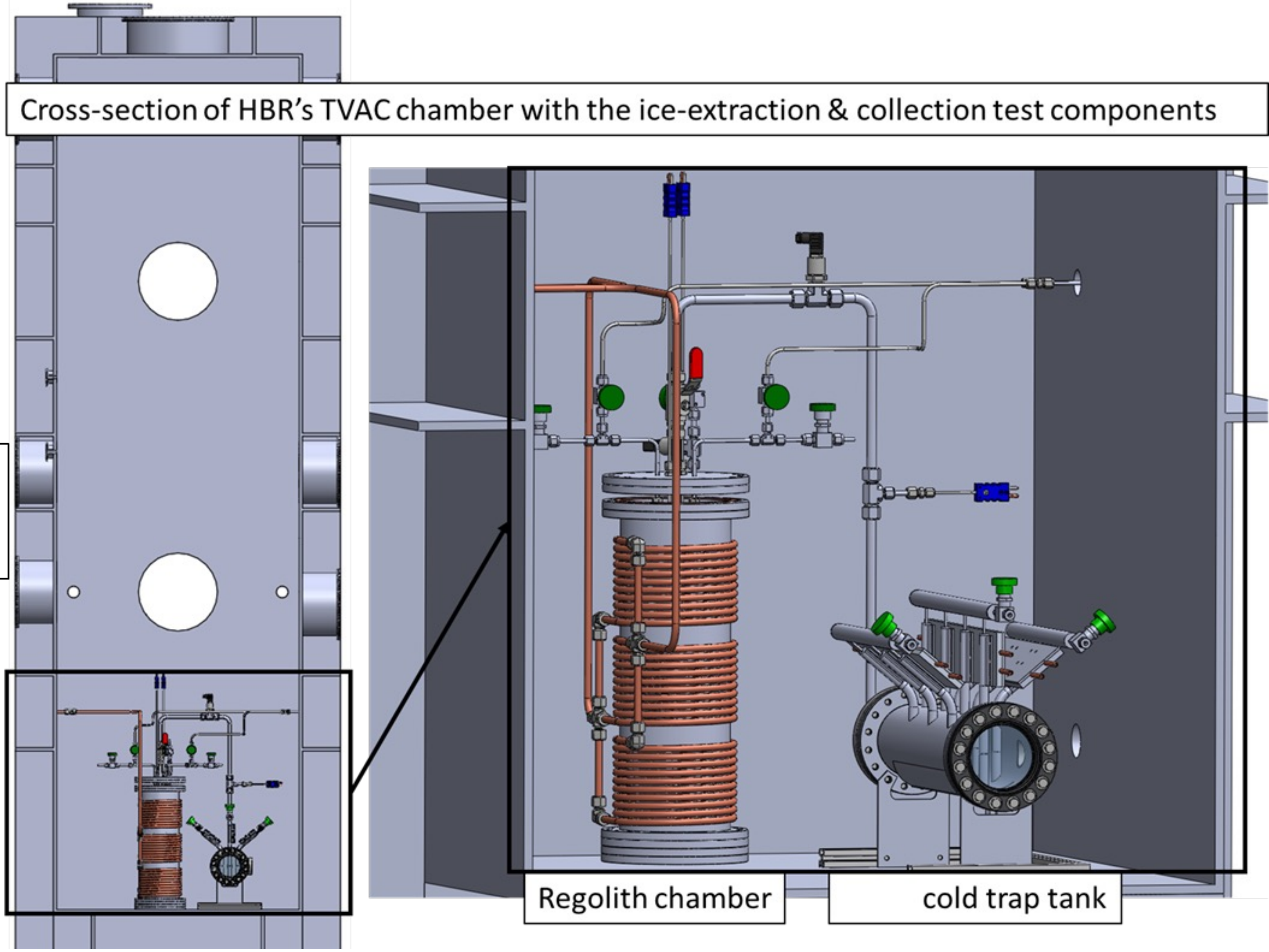
Ice Collection and Deicing modes of the VCHP Cold Trap Tank

- Functionality: ice collection and deicing modes of the VCHP cold trap tank, demonstrated in Phase I is shown here
- Functionality characterization of the VCHP cold trap tank will be undertaken in the ongoing performance period

Conclusions & Near Term Plans

Scale-up thermal corer





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Thank you for your time

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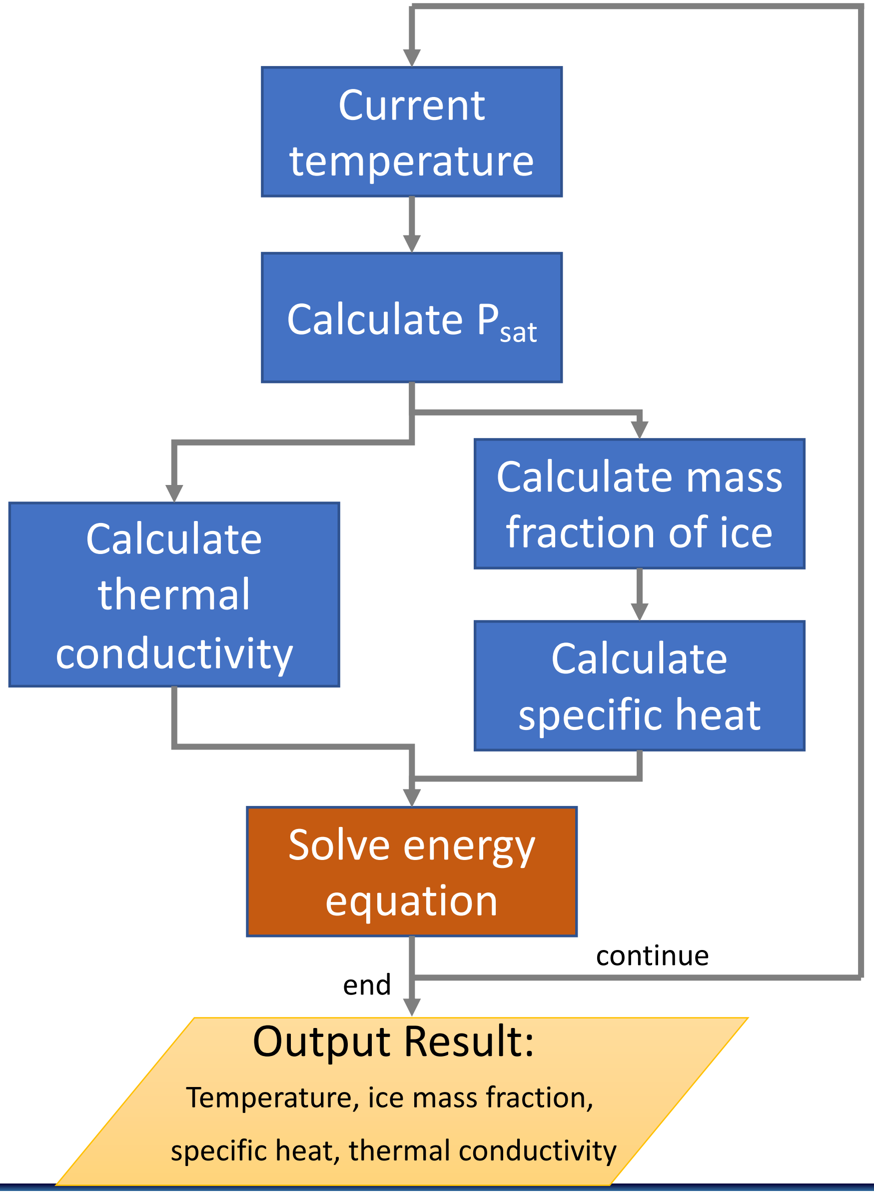
Calculation Flow Chart

- The thermal corer model is conduction based.
  - No vapor flow
  - No gravity
- The material properties of icy-soil are modeled as a function of temperature using user defined function (UDF)
  - Saturation pressure
  - Mass fraction of ice
  - Specific heat
  - Thermal conductivity
- Ansys-FLUENT will use the equations in UDFs to calculate icy-soil properties based on current temperature, and use those properties to solve energy equation to update temperature for the next time step.



Properties of icy-soil

- Specific heat of icy regolith (before phase transition) is a function of specific heat and mass fraction of dry regolith and ice:

$$\boldsymbol{C_P(T) = w_R C_{P_R} + w_{ice} C_{P_{ice}}}$$

$$C_{P_R}(T) = -23.173 + 2.127T + 0.015T^2 - 7.3699\times10^{-5}T^3 + 9.6552\cdot10^{-8}T^4$$
$$C_{P_{ice}}(T) = -100.5 + 11.43T + 7.101\cdot10^{-3}T^2 - 3.987\cdot10^{-4}T^3 + 2.075\cdot10^{-6}T^4 - 3.2\cdot10^{-9}T^5$$

- Saturation pressure of sublimated ice:

$$\boldsymbol{P_{sat}(T) = 14050.7T^{3.53068}\exp\left(-\frac{5723.265}{T} - 0.00728332T\right)}$$

Thermal Conductivity of Icy-soil

- Thermal conductivity of icy-soil can vary from 1e-3 to 1 W/m-K, and is a function of porosity, pressure, and temperature:

$$k(T,P,\nu) = -k_1 e^{(-k_4\nu)}\left(1 - k_5 T^3\right) + k_6 \hat{P}^{(k_2 - k_3\nu)} e^{\left(-k_7\nu + (k_8\nu - k_9) Ln^2 \hat{P}\right)}$$

  - We use a constant porosity of 0.3 in this case.

$$\hat{P} = \mathrm{Max}(P, P_0)$$

$$P_0 = 13.68508622330367 \text{ Pa}$$

$$k_1 = 3.419683995668$$

$$k_2 = 1.3409114952195769$$

$$k_3 = 0.680957757428219$$

$$k_4 = 2.8543969429430347$$

$$k_5 = 0.000000037037037037$$

$$k_6 = 0.799089591748905$$

$$k_7 = 2.637142687697802$$

$$k_8 = 0.024344154876476995$$

$$k_9 = 0.04793741867125248$$

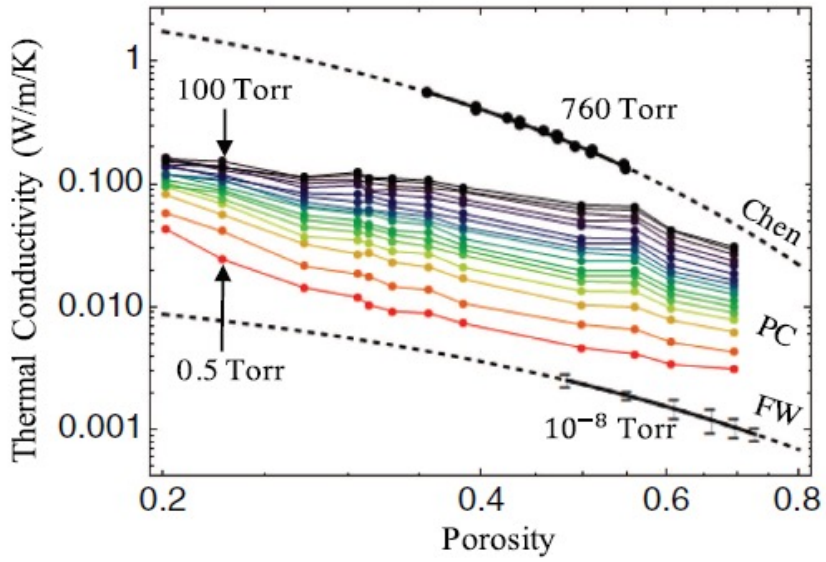


Fig. 8. (Color) Thermal conductivity versus porosity at different pore pressures, comparing the three data sets.

(Ref. P.T. Metzger, Kris Zacny et al.
Thermal Extraction of Volatiles from Lunar and Asteroid Regolith in Axisymmetric Crank-Nicolson Modeling" ASCE 2020)

Ice sublimation from solid to vapor

- <u>Mass fraction</u> is calculated from the phase transition equation:

$$m_{H2Ov}(t+dt) = m_{H2Ov}(t) + [P_{sat}(T(t)) - P(t)] \times \sqrt{\left(\frac{M_w}{2\pi \hat{R} T(t)}\right)} \times dt \times A_{core} \times \alpha$$

- The sublimation coefficient α is a function of morphology of the icy regolith, such as non-uniform ice distribution, porosity and permeability. [Schieber 2019], [Wasilewski 2021]
  - α should fine-tuned from experimental results
- During sublimation, the specific heat of icy-regolith is dominating by the latent heat of sublimation. An artificial specific heat $\widehat{C_P}$ is introduced:

$$\widehat{C_P}(T) = w_{ice}\frac{L_s}{\Delta T}$$

- w_{ice} = mass fraction
- L_s = latent heat
- ΔT = temperature window of phase transition (2K – 5K), depends on morphology of icy regolith, fine-tuned from experiment [Brisset 2020]